PCAS #12 Review

The Past is the Key to the Future

How will West Antarctica Ice sheet respond to the current climatic warming?

by Chris Mckenzie

Photo: ANDRILL project drilling for sediments that hold the secret to Antarctica's past climates.

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Introduction

The West Antarctica Ice Sheet (WAIS) is warming and is predicted to continue for decades to come (IPCC, 2007). How will WAIS respond to this warming? To answer this question we need to know how it responded to climate changes in the geological past. One of the best places to find this is in the Ross Sea, which is a depositional basin that has a record of all the sediments coming off Antarctica over millions of years (Chapman, et al. 2006).

Many coring programs have drilled in the Ross Sea, with the ANDRILL (ANtarctica DRILLing) project being the most recent. It has unveiled much of Antarctica's climate for the last approximate 40 million years (Naish, 2008). These Ross Sea coring projects have given us an understanding of how much ice was present on Antarctica during a given global CO_2 concentration and global temperature in the past (Foreman et al. 2007). They also show Antartica's past climate range supported forests through to glaciations (Chapman, et al. 2006).

The data retrieved from these drilled sediments can be incorporated into mathematical models which give insight to the extent of the WAIS in the near future.

Geology of Antarctica

In contrast to other continents, the rock of Antarctica is roughly 99% covered by ice, which is up to 4700 metres thick (Riffenburgh, 2007). This means all the geological knowledge of Antarctica is based on less than 1% of the continental area, which itself hasn't been fully investigated. Approximately half of the continent has been surveyed remotely, chiefly by aeromagnetic and gravimetric surveys (Riffenburgh, 2007).

Geological History

A basic understanding of Antarctica's geological history provides an understanding of why the Ross Sea is a good place for drilling.

This summary of the geological history begins with the early Palaeozic Granite (500+Ma) which were overlain by sediments that include fossils of early life forms like Archaeocyathans (sponges) (Riffenburgh, 2007). This was followed by a period of tectonic uplift and folding of both the early Palaeozoic Granite and sediments (Riffenburgh, 2007). Subsequent erosion of the uplift caused a large amount of time to be unrepresented (unconformity) (Riffenburgh, 2007).

The climate then warmed during the Devonian to Carboniferous periods (400-300Ma), depositing river sands and marine sediments which contained fossils (Riffenburgh, 2007).

The Permian Glaciation (300-280Ma) followed this warming which deposited glacial sediment due to cooling (Riffenburgh, 2007). After the glaciations during the Permain and Triassic, the climate warmed again depositing river sands and coal beds, which indicated the presence of forests and animals (Riffenburgh, 2007). When Pangea was breaking up (200-180Ma), rifting (spreading plates) and drifting of Antarctica caused intrusions of Igneous rocks (dykes) and volcanoes (Riffenburgh, 2007). Tilting and faulting then followed which subsequently caused erosion of the volcanoes and surrounding rock, representing another unconformity (Riffenburgh, 2007).

Tertiary sediments (<65Ma) which are mostly marine sediments were deposited on top of this unconformity (Riffenburgh, 2007). The development of ice sheets (34-15Ma) and another period of mountain building caused much of these tertiary sediments to be eroded (Riffenburgh, 2007). This eroded sediment consequently was deposited into basins, such as the Ross Sea. Volcanic activity also resumed (15Ma to present) as we see today. The Cenozoic (65Ma to present) rocks which have been deposited in the basins give an indication of Antarctica's response to similar climate changes as we see today, but they are located offshore.

The Ross Island volcanic complex has been increasing in size for the last approximate 4.6Ma, with most recent development during the last 1Ma, resulting in the formation of 3794m high composite vent of Mt Erebus (Horgan et al., 2005). This loading on the lithosphere has lowered the surrounding periphery of the volcanic vents, due to flexure of the crust (Horgan et al, 2005). This area is subsequently prone to even more sediment deposition.

This poses a problem, as the only way to get to them is by drilling.

Past Drilling Projects

There have been several drilling projects since the 1970's that have retrieved these tertiary sediments.

The first was the Dry Valleys Drilling Project (1972-1975) which was the first to attempt drilling these sediments, where fourteen holes were drilled in the Dry Valleys (Torii, 1981). The results furthered the understanding of the glacial and geological history at that time (Torii, 1981).

The second was the McMurdo Sound Sediment and Tectonic Study (MSSTS) that was conducted in the 1978-79 season (Barrett & McKelvey, 1986). This project was aimed at obtaining a record of the early history of EAIS and to date the initiation of the Ross Sea region (Barrett & McKelvey, 1986). Results were inconclusive due to the shallow depth of the drillingbeing 229.6m below the sea floor and the fact that only 44% of the sample core was recovered (Barrett & McKelvey, 1986). Identification of glacial advances 30 to 24 million years ago were identified, giving some insight into the dynamic nature of the ice sheets (Barrett & McKelvey, 1986).

Antarctic Cenozoic history was better understood from the CIROS project which drilled between Oct. 16-Nov. 14, 1986 (Barrett, 1989). This drilling project was very successful in that 98% of the sample core was recovered involving drilling to a depth of 702 meters (Barrett, 1989). They had a large range of findings from beech leaves to the discovery of a high geothermal gradient, dueto the rifting in the Ross Sea (Barrett, 1989).

The Cape Roberts Project (CRP) (1995-2000) drilled back through 1.5km of sediment that showed progressive cooling of Antarctica causing the disappearance of forests and the establishment of permanent ice sheets (Majewski, 2000). The major goal of the project was to find the Early Cenozoic hothouse to icehouse climate transition in the sediment core, which was not achieved (Majewski, 2000).

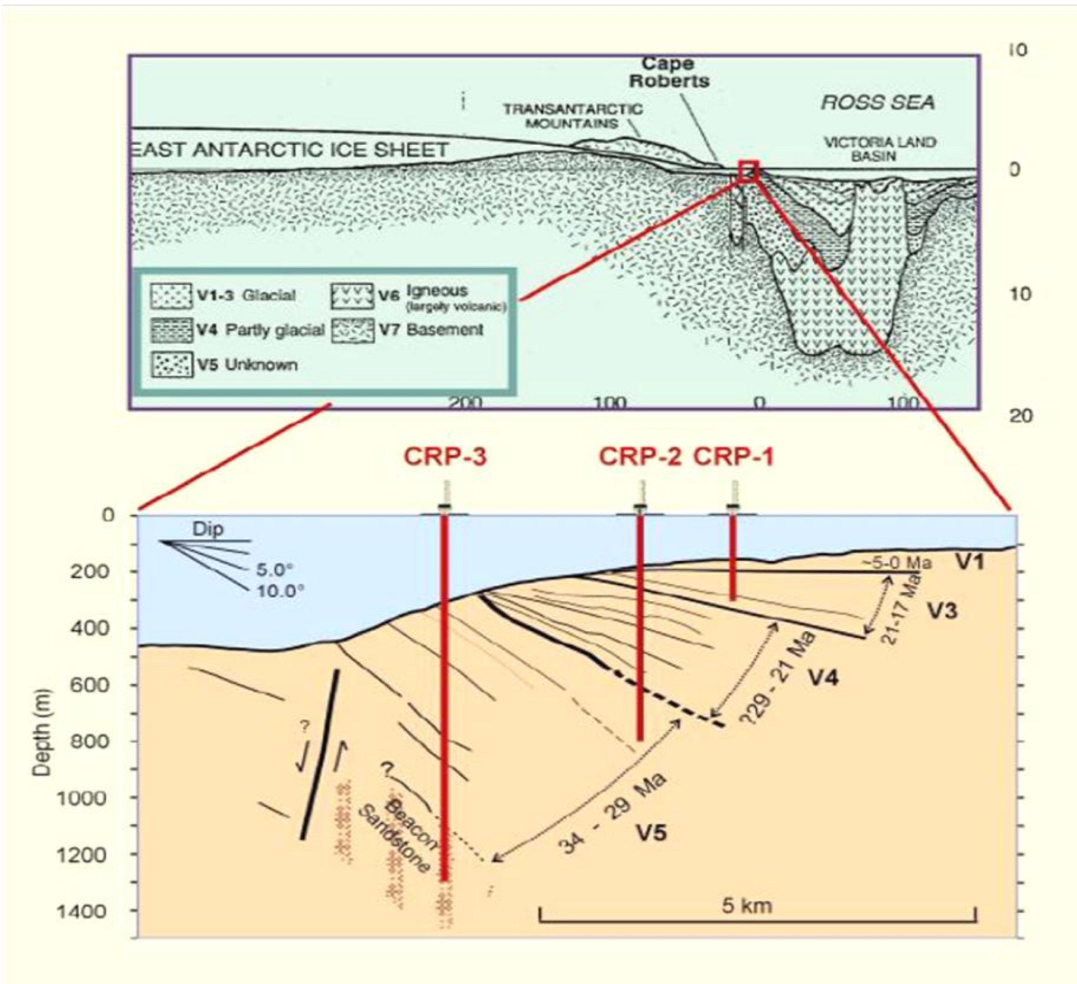

Figure 1, CRP showing the cross sectional location of the three drill holes, sediment ages and basic geology of the drill sites (Majewski, 2000).

ANDRILL

The current drilling project ANDRILL drilled in the McMurdo Sound to recover new sections of Cenozoic strata in locations where ice sheet oscillations can be determined.

This project essentially refines previous findings about the relationship between atmospheric carbon dioxide concentration, atmospheric and oceanic temperatures, sea level rise and natural cycles in Earth's orbit around the Sun, through the study of sediment and rock cores that are a geological archive of past climate.

The project had 5 aims: 1) glacial transitions in the development of the ice sheet, 2) analysing periods of climate warmth, 3) climate variability from Milankovitch cycles, and the role ice cover on the oceans, 4) polar biota, and 5) structural geology of the area (Florindo et al., 2003). For the team to achieve these goals they first did a geophysical survey, using gravity, magnetic and seismic surveys (Florindo et al., 2003). This provided the location for drilling for the desired lithological strata (Florindo et al., 2003). Secondly, drilling occurred over four seasons to obtain the stratigraphic sections. Thirdly, findings were incorporated into climate, glaciological and oceanographic models, to constrain estimates of Cenozoic ice volume variability (Florindo et al., 2003).

Sediment Core Contents

The recovered cores contained a range of lithologies, including sandstones, siliciclastic?? diamictites , poorly sorted deposits associated with glacial processes, mudstones, diatomites and volcanic deposits (Morin et al, 2007).

Environment of Deposition

The different types of sediments all indicate different environments of deposition. The diatomites indicated open marine setting as the waters would have been warm enough to support marine life dominated by diatoms. During interglacials, mudstones and tubidities are deposited because of the open ocean environment (Naish et al., 2007). The diamictites, conglomerates and sandstones indicate glacial conditions.

The glacial erosion surface created by the advancing ice sheet on the seabed marks the beginning of the cycle (Naish et al., 2007). During the interglacial the grounding line retreats, sometimes with rapid transitions to open-ocean environment (Dunbar et al., 2007). The ice then re-advances creating another glacial erosion surface.

During the glacial periods the grounding line of the ice sheet would have been located hundreds of km north the drill sites. During interglacials, such as today, the site was either covered by ice shelf or lay in open waters, depositing diatoms, terrigenous mud and debris from icebergs (Naish et al., 2009)

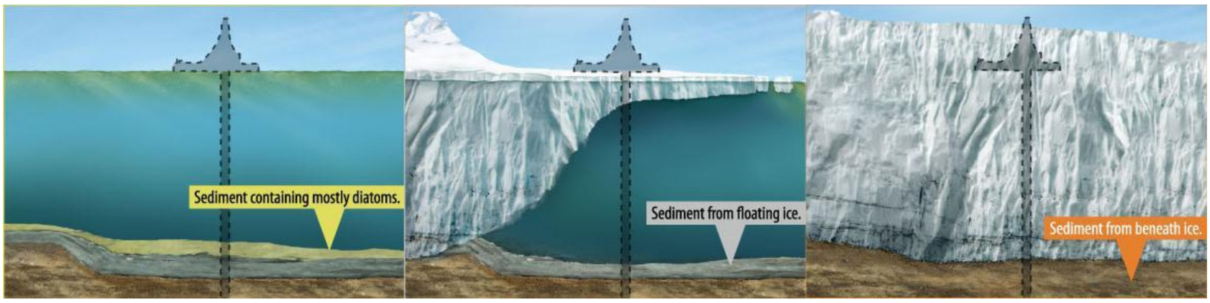

Figure 2, Illustration showing how interglacial to full glacial condition can deposit diatomite and diamictites. The shaded area represents the location of the ANDRILL drilling platform.

The composition of the clast deposits indicate that the ice originated in the southern Transantarctic Mountains (TAM), usually from the Byrd and Skelton glaciers (Naish et al., 2007). From these observations, one would assume that the results would reflect EAIS fluctuations on ice volume, but Denton and Hughes, 2002 demonstrated that significant ice volume from WAIS is needed to force the southern outlet glaciers into the McMurdo region. Denton and Hughes, 2002 also demonstrated that significant ice flow off WAIS is needed to sustain the Ross Ice Shelf. The sedimentary cycles are thus asserted to be responses to the expansion and contraction of the WAIS with relation with fluctuations in the flow of TAM outlet glaciers (Naish et al., 2007).

From the 1285m long AND-1B core more than 60 glacial-marine sequences were recognized, which were bound together by surfaces of erosion from ice scour during glacials (Morin et al., 2007). Some sequences were largely eroded from the glacial advances (Morin et al, 2007).

Calcareous plankton such as foraminifera have a sand-sized shell, that incorporates chemical elements and isotopes from the ocean. For example, the ratio of magnesium to calcium (Mg/Ca) relates to ocean temperature, and the ratio of barium to aluminium (Ba/Al) gives an insight into ocean fertility that involves the production of plant and animal plankton – the foundation of the marine food chain (Scherer et al., 2007).

Paleoclimatology

Evidence for the climate of Antarctica during the late Cenozoic (the past ~15Ma) is poorly known (Naish et al, 2007). Interpretations of oxygen isotope records from deep sea cores have provided the majority of current knowledge about the role of ice-sheet responses to climate changes (Naish et al, 2007).

Results from the ANDRILL cores provide direct physical calibration for low-latitude continental margin sea level records, deep-sea isotope records, numerical ice sheet and climate models (Naish et al., 2007). This is important because there are current difficulties in predicting the dynamic response of ice sheets to global warming.

From data collected by the deep-ocean isotope record, it is thought 14Ma ago Antarctica expanded to its current extent (Zachos et al., (2001). During this time EAIS has remained mostly intact, but oscillations in the ice extent occur (Naish et al., 2007). Sea level changes were mostly caused by WAIS and northern hemisphere ice sheet fluctuations.

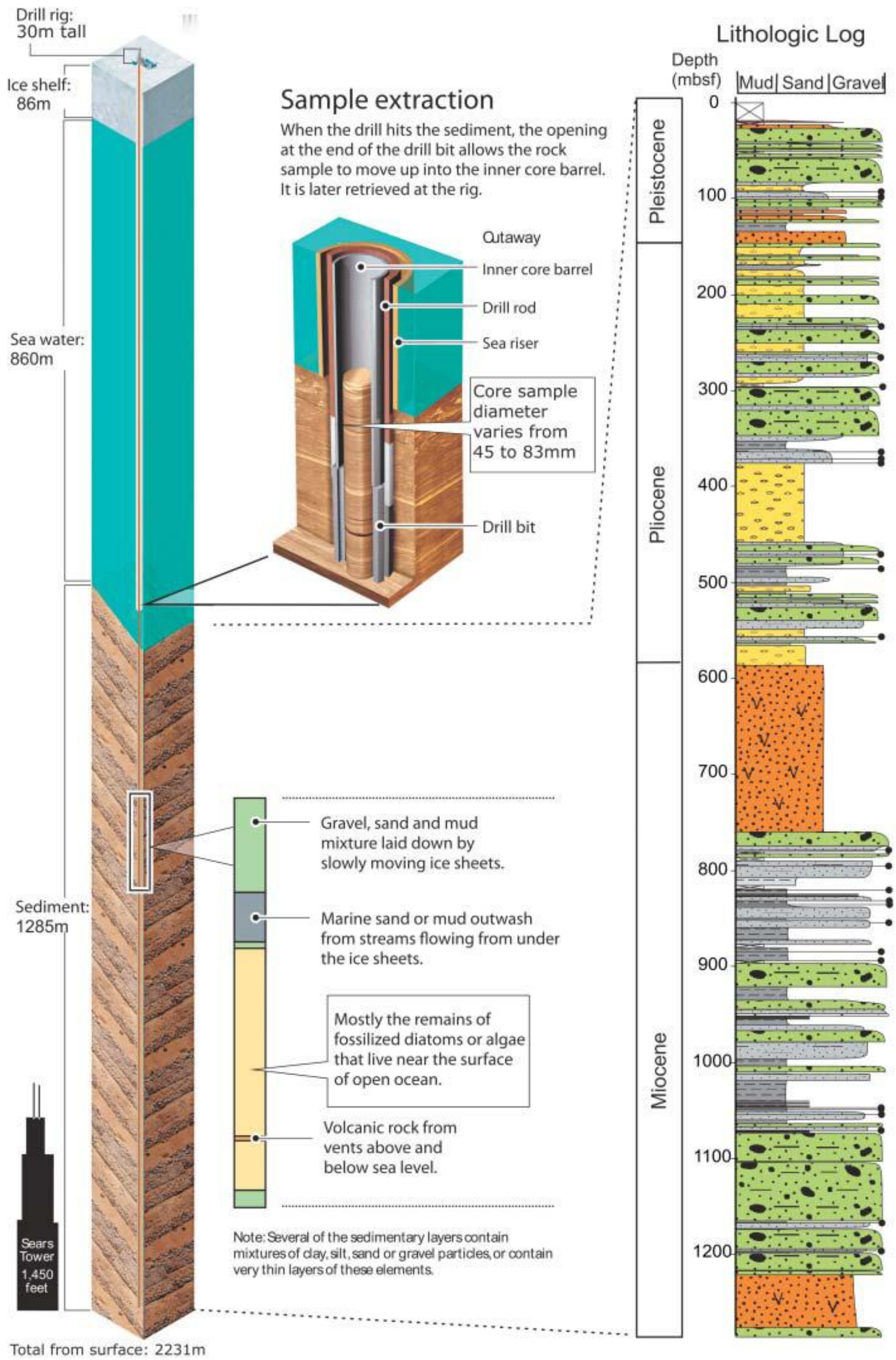

Figure 3. From the stratigraphic log the glacial advances are represented by diamictites represented in green. Glacial retreats are illustrated by the yellow diatomite beds and the gray marine mudstone. The orange layers in the stratigraphic column are the volcanic deposits. This illustration is a good example how sediments from the cores show the cyclic nature of the changing ice extent, driven by climatic changes (Naish et al., 2007a).

The core showed four different phases of late Cenozoic climate evolution. The first phase was 13.5-10 million years ago, where the climate would have been cool, due to the large amount of glacial diamictite beds (Naish et al., 2007). The interglacial periods during this time deposited glacimarine mudstones (Naish et al., 2007). Phase two (9-6Ma) would have been a warm period implied by the submarine outwash deposits (Naish et al., 2007). During the glacial maxima the ice sheet was grounded at the site, indicating huge changes in ice sheet volume (Naish et al., 2007). The Pliocene period represents the third phase where the interglacials display pelagic diatomite in beds as thick as 80 meters, indicating high phytoplankton productivity (Naish et al., 2007). During late Pliocene (2.6-2.2Ma) abrupt transitions between subglacial diamictites and open marine diatomites give a good insight into glacial-climate interactions (Naish et al., 2007). Phase four represents the last 800,000 years where extensive ice sheets dominated (Naish et al., 2007),and only thin units of volcaniclastic, mudstone and sandstone sediments occurred during the interglacial periods (Dunbar et al., 2007).

Dating

The stratagraphic layers need to be dated so the data can be correlated to existing models. Dating of the ANDRILL cores were constructed from diatom biostratigraphy, radiometric ageing of the volcanic material and correlating with the magnetic polarity (Wilson et al, 2007). This dating shows a range of deposition rates, from 1m per 1000 years to missing gaps in time as great as 1Ma (Wilson et al., 2007).

AND-1B drill core had 1309 samples taken to determine the Natural remnant magnetisation used for dating (Wilson et al., 2007). The beds which contained poorly consolidated diamictite strata could not be sampled (Wilson et al., 2007). From the sampled core, eight normal and seven reversed polarities were measured (Wilson et al., 2007). This was correlated to the Geomagnetic Time Scale, which is used for dating.

Seismic Surveys

The seismic reflection data undertaken on the south side of Ross Island revealed well stratified sediment succession to depths of 1.2km, which thicken and dip towards Ross Island (Horgan et al., 2005). Erosion of these sediments from ice grounding during glacial expansions of the WAIS has largely escaped erosion because the phases of load-induced subsidence may have periodically over deepened the moat (Horgan et al., 2005).

Conclusions from ANDRILL

Data from the core indicate the advance and retreat of WAIS numerous times in the response to the climate changes chiefly driven by Milakovich cycles (changes in Earth's orbit, tilt and wobble of axis, which differes the amount of solar radiation). Approximately four million years ago when Earth's temperature was 3°C warmer than present and Co2 levels were 400 parts per million, WAIS was mostly submerged by ocean. (Naish et al, 2009).

They found a short warm period 15.7 million years ago, evident from fossils, algae and pollen of woody plants, indicating the average temperature during summer would have been roughly 10 degrees Celsius in the McMurdo Sound. It was an abrupt warming that serves as an analogue for understanding future ice sheet and climate behaviour.

Predicting the beginnings of the WAIS collapse is still not known with any credible accuracy, chiefly because it depends on future Co2 levels (Naish et al, 2009).

Modelling

The results of the ANDRILL project provide calibration for various models. Pollard & DeConto, 2009 have modelled WAIS growth and collapse throughout the past five million years. They used a combined of ice sheet/ice shelf model to simulate Antarctic ice sheet variations over the last five million years. The results of the model show grounding line extents near the continental shelf break, intermediate states similar to today and dramatic retreats, leaving isolated ice caps on the West Antarctic Islands.

Transitions between collapsed, intermediate and glacial states are relatively rapid, taking one to several thousand years (Pollard & DeConto, 2009). The model has been correlated with AND-1B, which provides greater accuracy in the models predictions. The result of this model shows that each time WAIS collapsed, the margins of EAIS also melt, and this combined effect would raise sea levels by seven metres (Pollard & DeConto, 2009). The model showed that collapses of WAIS would take one to three of thousands of years to collapse completely (Pollard & DeConto, 2009). From the geological and modelling data it is clear that ocean temperature play a large role in melting of ice shelves, thus ultimately causing there collapse (Pollard & DeConto, 2009).

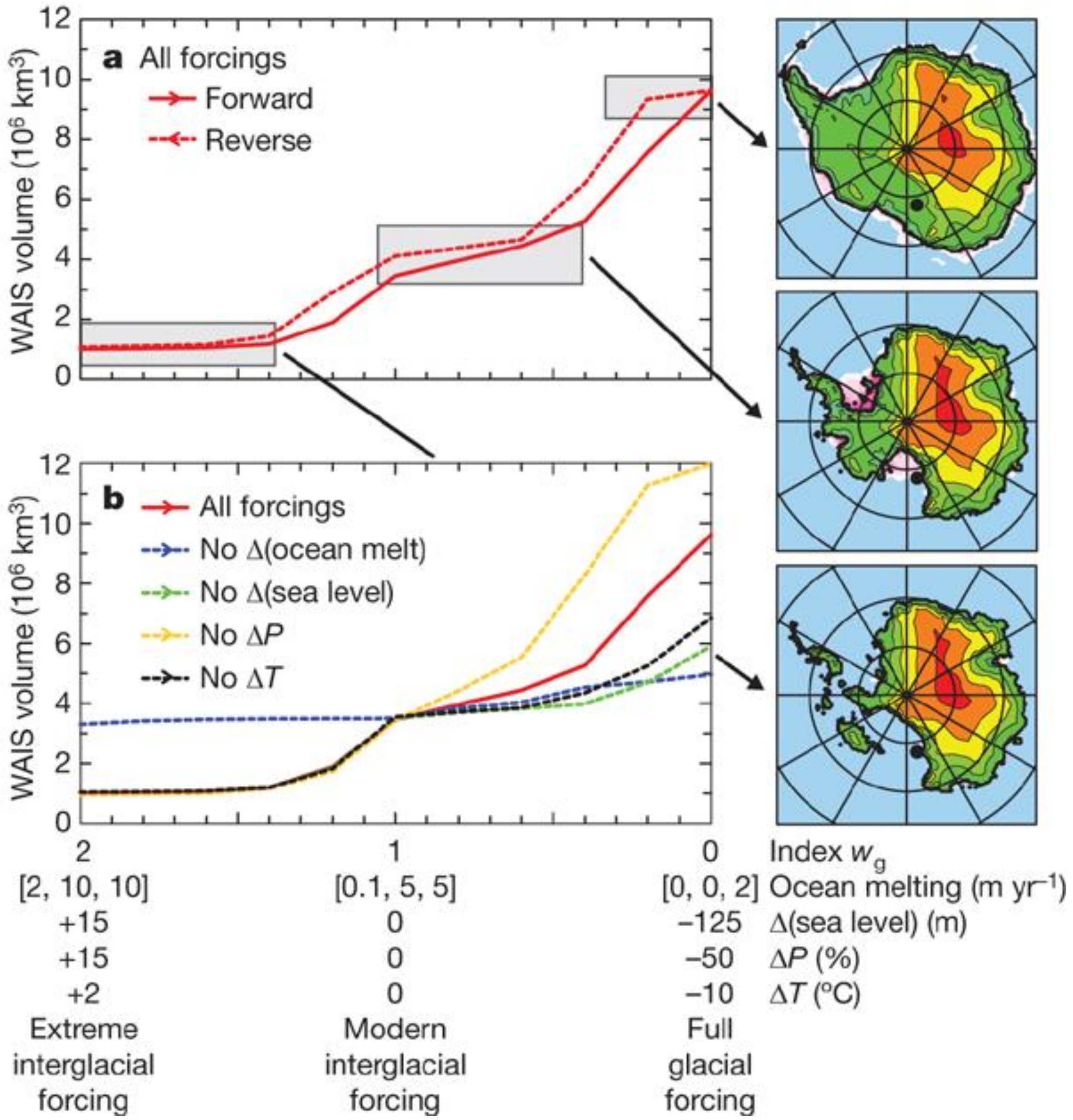

Figure 4, This diagram shows how different environmental forcing effect the WAIS during warmer and cooler periods. The forcing that is considered in the model is melting caused by ocean, sea level, precipitation and temperature. The y-axis is WAIS volume and climate forcing on x-axis. The first diagram (a) shows the amount of ice present on ice sheet when climate is warming (solid red line) and cooling (dashed red line). The second diagram (b) shows the effect on WAIS volume if one forcing is held constant at modern values. For example it can be seen with no change in current precipitation, WAIS in a full glacial would have a far greater ice volume than any other forcing (Pollard & DeConto, 2009).

Conclusion

Incorporating the results from the ANDRILL cores with existing 18O in deep sea cores increases the accuracy of past ice volumes on Antarctica (figure 5).

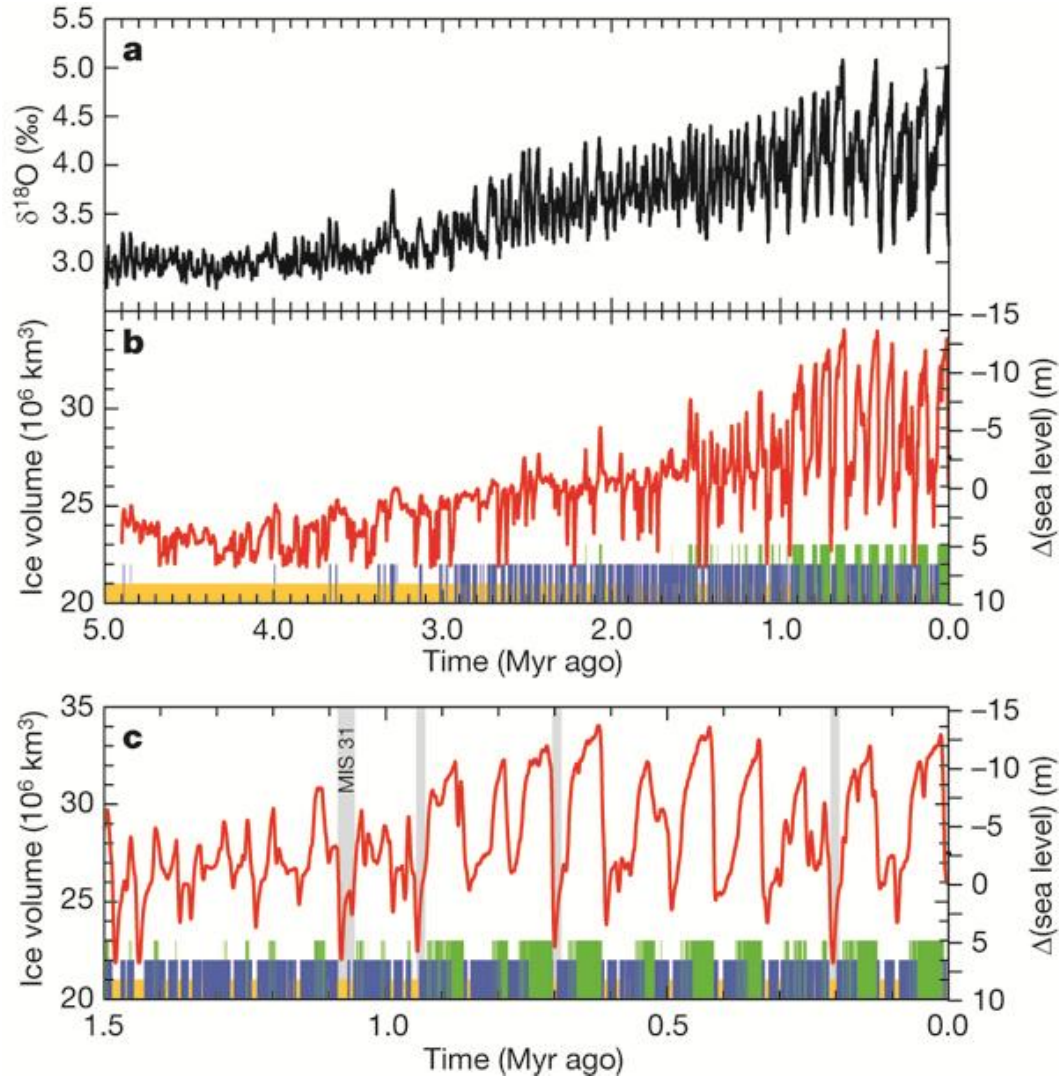

Figure 5, The first graph (a) shows the stacked deep sea core benthic 18O and the second (b) shows the long term simulation of the total Antarctic ice volume, with the equivalent changes in global sea level. The results of the AND-1B are displayed at the bottom where, green represents grounded ice, blue floating ice shelf and yellow representing openocean. This also represented in the bottom diagram (c) where the same scale is smaller, the grey shading represents periods of super interglacials (Pollard & DeConto, 2009).

ANDRILL's core has shown clear evidence that WAIS can collapse rapidly as shown in *figure* 6.

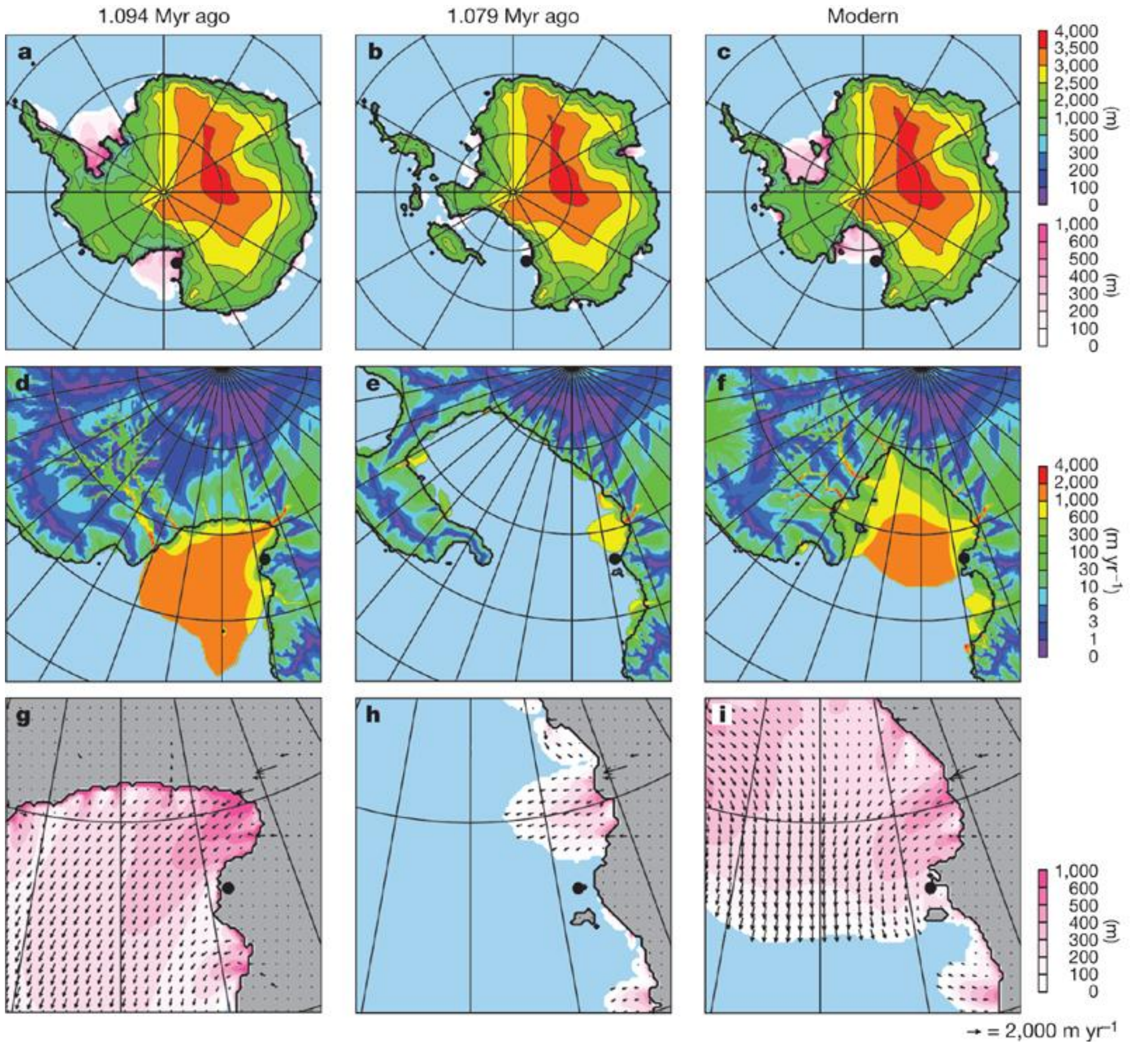

Figure 6, The left column represents 1.094 Million years (Myr) ago, middle 1.079 Myr ago and right column is today. a-c, Show the grounded ice elevations and floating ice thicknesses. d-f, surface ice speed. g-i, floating ice thickness and velocity. The black dot is the location of the AND-1B (Pollard & DeConto, 2009).

Results from ANDRILL show that WAIS had collapsed in the past when the temperature is 3°C warmer than today and CO_2 concentrations are 400ppm (Naish et al, 2009). This is most likely going to occur again by the end of the century (IPCC, 2007). Results from incorporating ANDRILL's data into prediction models show similar collapses of the WAIS and 7 metre increases in sea levels (Pollard & DeConto, 2009). Collapses of the WAIS have been abrupt (~<500 years) in the past, thus could be just as abrupt today, but large uncertainties still remain (Naish et al., 2009). The direct evidence of WAIS stability from the ANDRILL cores shows that it is highly sensitive to climate warming, so man needs to stabilize the climate while we still have a little time.

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